TEST AND MESOSCOPIC FINITE ELEMENT ANALYSIS ON MECHANICAL PROPERTIES DEGRADATION OF AGED COATED FABRICS

STRUCTURAL MEMBRANES 2017

QILIN ZHANG*, YUNTING LI†

*College of Civil Engineering
Tongji University
200092 Shanghai, China.
E-mail: zhangqilin@tongji.edu.cn

† College of Civil Engineering
Tongji University
200092 Shanghai, China.
E-mail: liyunting0715@sina.com

Key words: PVDF-coated Fabrics, Ageing Behavior, Mechanical Property, Mesoscopic Finite Element Analysis.

Summary. In this paper the mechanical properties degradation of aged coated fabrics is investigated. Tests on the tension strength and the tearing strength of the aged fabrics are carried out, which is from the membrane roof of Qingdao Stadium used for more than 13 years. The strength degradation degrees of the aged fabrics are obtained. Due to the configuration of fabrics the numerical simulation on its stress state as well as its fracture process and mechanism is very difficult. In this paper, a mesoscopic finite element model for plain woven fabrics stress analysis is established based on woven configuration fabric cells. The numerical analysis shows that a firm yarn-yarn connection at interlacing point would make fabrics has high shear stiffness and concentrates tensile stress on the edge of the fabrics in which applied load. It coincides with the bi-axial tensile test, in which cruciform specimen fracture always at the arms instead of core area. Finally the fracture criterion is built up for new and aged fabrics on the basis of the test and analysis results of this paper.

1 INTRODUCTION

Membrane structure, with many advantages including a light weight, good light transmission, flexible stretch, strong sense of shape and great architectural performance, is well received and has been widely used in public shelter structures. Built on a bend in the River Thames in Greenwich, London, the Millennium Dome is one of the most famous Britain's landmarks. The world's most luxurious United Arab Emirates BurjAl-Arab hotel in Dubai is a double-layer membrane structure of the building. It is built on a man-made island with a light graceful sailboat styling shape and integrated into the surrounding landscape. Besides, the membrane structures are preferred in the many public buildings, such as Stadium and Airport. However, the membrane structure also has essential shortcoming, that is, compared with the steel, concrete, glass and other building material, membrane material is more easily aging and could cause the destruction of the structure. To ensure safety, aging of membrane materials is an important subject.

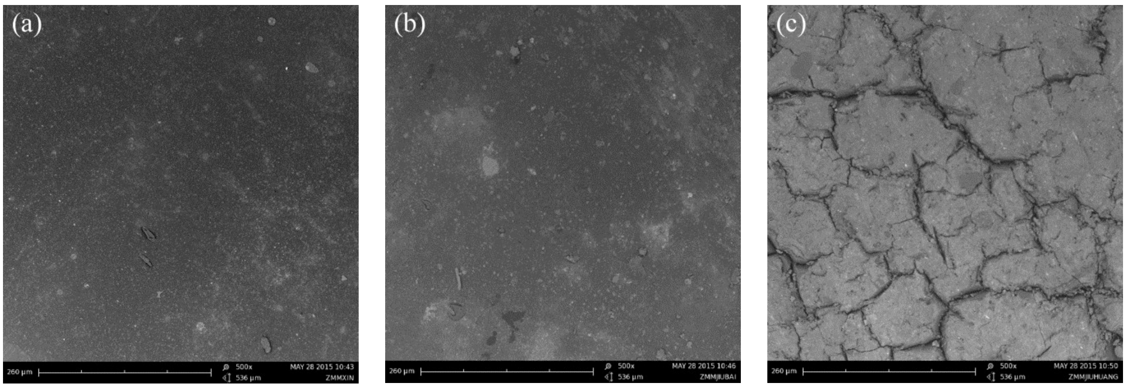
Many research on the effects of different factors on the aging of membrane materials have been carried out with artificial accelerated ageing method [1-8] or outdoor ageing method[9-12]. These studies are the basis for the study of aging properties of membrane materials. For further understanding of material aging, the aging coated fabrics removed from a stadium been selected as research objects, a list of mechanical tests are carried out. To figure out its aging mechanism, numerical simulations are also performed. This paper consists of two main parts, experiment study and numerical analysis.

2 AGING PROPERTIES OF PVDF

To evaluate the durability of coated fabrics after aging in a structure outdoor, a series of contrast experiments was carries out between the natural ageing coated fabrics removed from a stadium built in 2007 and the new specimens of the same type of coated fabrics. Mechanical properties of coated fabrics, including tensile, tearing and bonding strength, are tested according to DG/T J082019-2007 (2007)[13]. The main test results and analysis are as follows [14].

2.1 Coating

The reduction of brightness at the sunny side is 56.42%, while that at the shaded side is 30%. According to the microscopic morphology of the fabric coatings (Fig. 1), the ageing coating at the shaded side has some bulges, but there is not crack and pulverization. However, the ageing coating at the sunny side is full of cracks, with bulges and pulverization. The color change and cracks caused by ageing at the sunny side is more severe than that at the shaded side. According to the aging principle of polymers， it is mainly due to the ageing mechanism of high polymer material, namely rupture of molecular chain (degradation) and crosslinking of macromolecular chain [15].



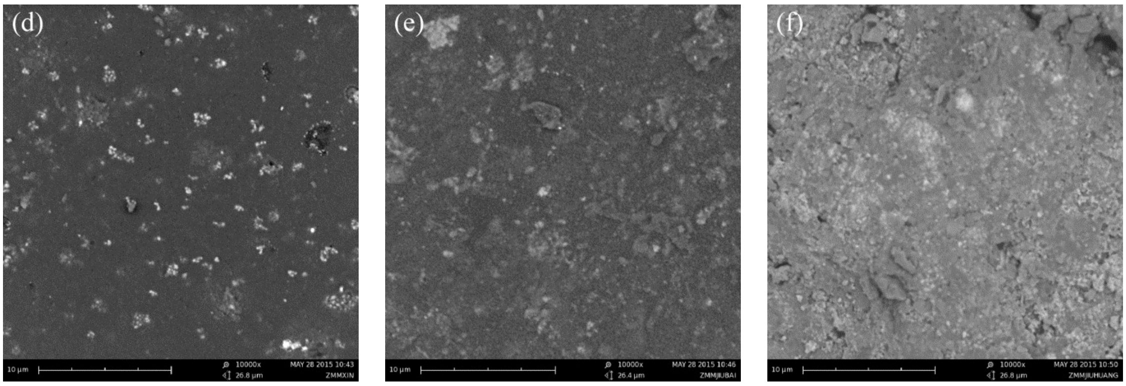


Figure 1: Photographs of the coating by SEM: (a) new coating×500 (b) ageing coating at the shaded side×500 (c) ageing coating at the sunny side ×500 (d) new coating×10000 (e) ageing coating at the shaded side×10000 (f) ageing coating at the sunny side ×10000

2.2 Force at failure & tearing strength

The results of force at failure and tearing strength tests are presented in Table 1. In warp direction, force at failure of the new fabrics is 8132 N/5 cm, while that of the ageing is 7329 N/5 cm. In weft direction, force at failure of the new fabrics is 7051 N/5 cm and that of the ageing one is 6792 N/5 cm. Test results show the force at failure of fabrics decreases by 9.9% in warp direction and decreases by 3.7%in weft direction. In warp direction, tearing strength of the new coated fabrics is 1217 N, while that of the ageing is 937 N. In weft direction, tearing strength of the new coated fabrics is 1163 N and that of the ageing is 818 N. Experimental results show that tearing strength of aging coated fabrics decreases by 23% in warp direction and 29.6% in weft direction. Possibility P of significant difference are 1.5E-18 and 2.8E-29 in warp and weft respectively, which are lower than 0.05. T-test proves that tearing strength of the new and aging material has notable difference in warp and weft directions. In addition, it can be found that the degradation of tearing strength is more obvious than that of force at failure, which is consistent with other researches [4, 8, 24].

Table 1: Force at failure testing results

Material	Tensile force (N/5cm)		Tearing strength (N)	
	Warp	Weft	Warp	Weft
New	8132	7051	1217	1163
Ageing	7329	6792	937	818
Reduction	9.9%	3.7%	23.0%	29.6%

3 NUMERICAL ANALYSIS

In order to analyse stress of aging membrane material. The numerical model of coated fabrics is built. There are three parts in this section. Stress characteristics of the coated yarn were analysed and tangential action at the interlaced point of fabrics was discussed. Besides, the effect of coating hardening on fabric was studied.

3.1 Method

Coated fabrics membrane can be analyzed on three scales: macroscopic, mesoscopic and microscopic. In this paper, modelling and analysis are on the mesoscopic. A yarn is the basic constituent material.

Modelling tool is Texgen which [16, 17] is developed by the Polymer Composites Group at the University of Nottingham as a modelling pre-processor for a variety of applications including solid mechanics. It provide a graphical user interface to define path, section shapes and dimensions of a yarn and discretize yarns by a built-in mesh generator.

In this paper, two weft yarns and two warp yarns are interlaced vertically to form a unit cell as fig. 2 shown. In Texgen, yarn path is represented by a spline S(u). As fig. 3 shown, 9 control points are defined and Natural cubic spline is selected. Section shape of yarns are lenticular according to SEM above. Width and height is 1.8 and 0.4 respectively. Other parameters are shown in the Table 2. Geometric information is according to SEM of the yarn.

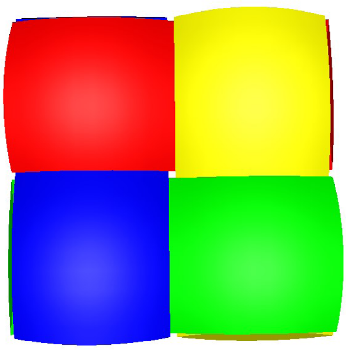


Figure 2: Unit cell

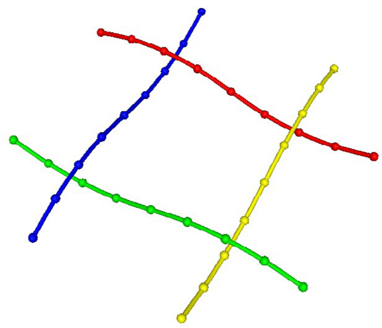


Figure 3: Yarn path and control points

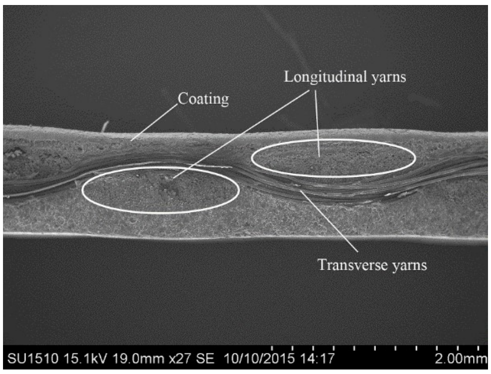


Figure 4: The cross section of ageing coated fabric

Table 2: Parameters of yarns

Parameters	Warp	Weft
Yarn linear density	0.0002002 kg/m	0.00011 kg/m
Fiber density	1.37g/cm^3	1.37g/cm^3
Total fiber area	0.146554mm^2	0.08052 mm^2
Fiber diameter	25μm	25μm
Fiber per yarn	300	165

Mechanical model of yarns are defined in Abaqus [18]. Tensile properties are defined using experimental data as isotropic hyperelastic materials. The stress-strain curves are shown in Figure 5. The Poisson's ratio is 0.4. The coating is defined as elastic material.

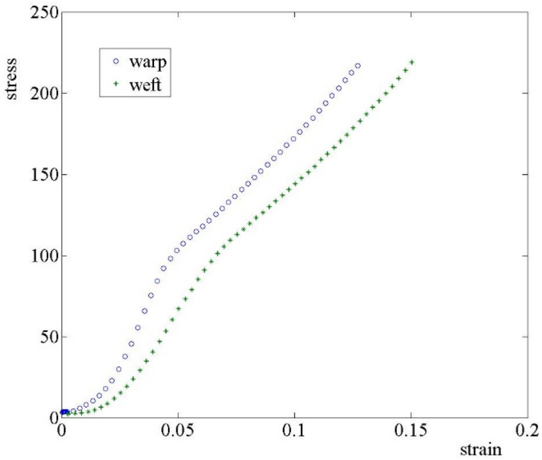
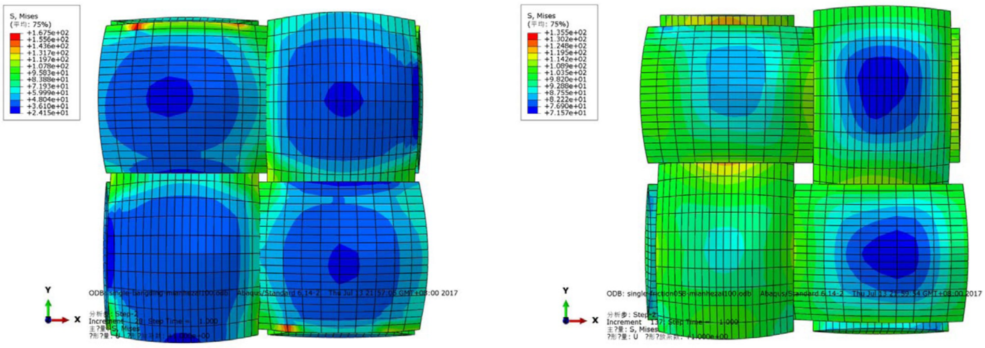


Figure 5: Stress-strain curves of yarns

3.2 Results and analysis

In the coating process of the fabric, there may be two modes of action in the intersection of warp and weft yarns. The first situation is that warp and weft yarns is bonded at the interlace points. The second is the coating material is not penetrated inside and there is only tangential friction at the interlace points. In this paper, the stress state of the yarn under tension in above two cases is compared and analysed.

From fig. 6-a, in the bonding mode, stress of the whole yarns are more concentrated at some location, while it is uniform in the friction-mode. In the bonding mode, the maximum and minimum values differ by 1/3, however, stress are kept at the same level in the friction mode. According above, when the yarns are independent at the interlace point, the fabrics would show a greater strength due to a reasonable stress distribution. After applied coating, if yarns of the fabrics bonding together, the stress of yarns concentrated in the free area between the interlace points and it reaches to the maximum at both ends of the lenticular section.



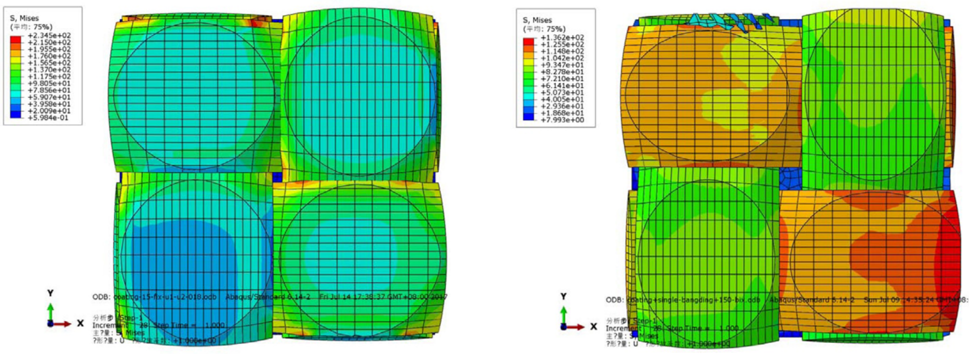
(a) Bonding together at interlace point (b) Friction model at interlace point

Figure 6: Stress nephogram of two models

Considering the modulus of elasticity changes when the coating is aged, the following sections compare the effect of the coating hardening on the internal stress of the fabric.

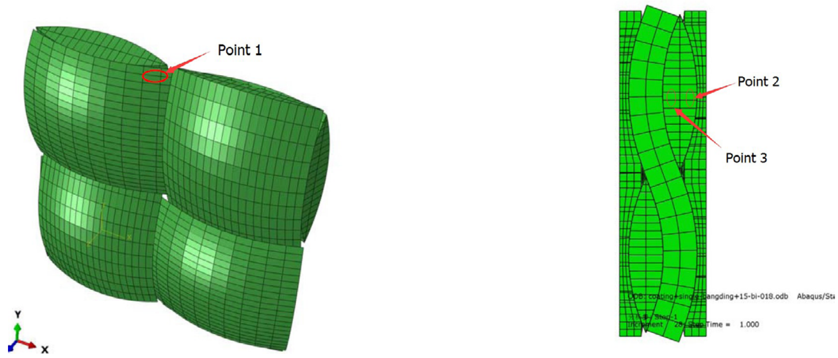
With two different elastic modulus of coating, stress of yarns in a unit cell are shown in Figure 7. In Figure 7-a, when elastic modulus of coating **E** is 15 MPa, the stress concentrate on the edge of a yarn. From Figure 7-b, when elastic modulus of coating **E** is 150 MPa, there is average distribution stress in a yarn. In addition, stress are contrasted at three typical positions of a yarn, as Figure 8 shown. Under the same load, stress-strain curves of three points on a yarn was show in Figure 9. From Figure 9-a, it is easy to find that there is a great difference at three points. However, in Figure 9-a, stress in the three positions is much closer. Hardening of the coating tend to a more equal distributions of stress. The improvement of stress concentration can make the yarn force more uniform and the fabric strength higher

It should be emphasized that the elastic modulus of the coating discussed above is much smaller than that of the yarn. If the modulus of coating and yarn on the same level, it will cause stress concentration in the coating and the bonding position, and the force condition needs a further studies.



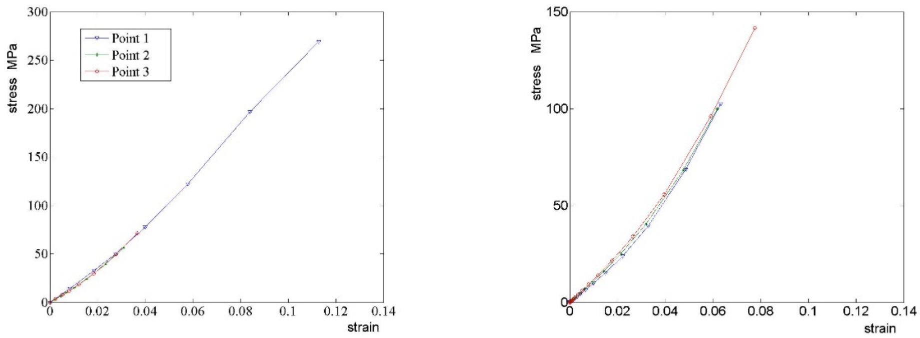
(a) Elastic modulus of coating **E**=15 MPa (b) Elastic modulus of coating **E**=150 MPa

Figure 7: Stress of two models



(a) Point 1 (b) Point 2 & a. Point 3

Figure 8: Typical position



(a) Elastic modulus of coating E=15MPa (b) Elastic modulus of coating E=150 MPa

Figure 9: Stress-strain curve

4 CONCLUSIONS

Based on the above research, the following conclusions are obtained:

- Aging coating has cracks, powder and other aging characteristics.
- Tensile strength of coated fabrics decrease by less than 10% and tearing strength decreased to 20%~30%
- Numerical analysis shows that tangential action at the interlaced point of fabrics greatly affect the distribution of stress. When the warp and weft are bonded at the interlace points, stress is concentrated on the edge of a yarn. If there is only friction in tangential at the interlace points, stress distribution of a yarn is more even.
- After aging, the hardening of the coating will lead to a more uniform stress distribution of the yarn. This may be one of the reasons why the tensile strength of the fabric does not decrease significantly after aging

REFERENCES

[1] Zhang YY. Effect of Temperature and Water Immersion on the Mechanical Properties of

Coated Fabrics. *Advanced Materials Research.* Vols.129-131(2010): 230-234.
[2] Real L P, Gardette J. Ageing and characterisation of PVC-based compounds utilised for exterior applications in the building construction field 1: Thermal ageing. *Polymer Testing.* 2001, 20(7): 779-787.
[3] Berdahl P, Akbari H, Levinson R, et al. Weathering of roofing materials – An overview. *Construction and Building Materials*. 2008, 22(4): 423-433.
[4] Razak H A, Chua C S, Toyoda H. Weatherability of coated fabrics as roofing material in tropical environment. *Building and Environment*. 2004, 39(1): 87-92.
[5] Chen ZR, Zhang QL, Xue WL. Experimental Research on Mechanical Properties of PVC Membrane after Ageing. *Proceedings of international Association for Shell and Spatial Structures,* Wroclaw, Poland, 2013.
[6] Kuai BL. Aging Tests of PVC Membrane Material. *Tensinet instanbul Symposium*, 2013
[7] Triki E, Arrieta C, Boukehili H, et al. Tear behavior of polyester-based coated textiles after thermo-oxidative aging. *Polymer Composites*. 2012, 33(6): 1007-1017.
[8] Andelko O, Haramina T. Effect of aging on mechanical properties of polymeric ripstop fabrics. *J. Polym*. 2012.
[9] Joneydi S, Khoddami A, Zadhoush A. Novel superhydrophobic top coating on surface modified PVC-coated fabric. *Progress in Organic Coatings*. 2013, 76(5): 821-826.
[10] Zhou S, Ding X, Wu L. Fabrication of ambient-curable superhydrophobic fluoropolysiloxane/TiO2 nanocomposite coatings with good mechanical properties and durability. *Progress in Organic Coatings.* 2013, 76(4): 563-570.
[11] Ahmed H. Improving UV Resistance of High Performance Fibers. *ProQuest Dissertation and Theses,* North Carolina State University, Raleigh, NC, 2011.
[12] Ambroziak A. Mechanical properties of PVDF-coated fabric under tensile tests. *J.Polym. Eng.* 2015; 35(4): 377-390.
[13] DGTJ08－2019－2007. Technical Specification for Inspection of Membrane Structures. Shanghai Construction and Traffic Committee: Shanghai, 2007.
[14] Li YT, Liu T, Yang B, et al. Effects of Natural Ageing on Mechanical Properties of PVDF-Coated Fabrics. *Structural Engineering International*. 2016, 26(4): 348-356.
[15] Wen JB. *Mechanical engineering materials*. Machinery Industry Press, 2009: 302.
[16] Long. H L L B. Modelling and simulating textile structures using TexGen. 2011.
[17] Lin H, Clifford M J, Long A C, et al. A finite element approach to the modelling of fabric mechanics and its application to virtual fabric design and testing. 2012.
[18] Al. H L X Z. Automated geometric modeling of textile structures. *Textile Research Journal.* 2012.